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Cropping Flax for Grain and Fiber: A Case-Study from Italy

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Abstract: Flax (*Linum usitatissimum* L.) can be grown both as an oil crop and as a fiber crop, and this offers new opportunities when included in the framework of a whole-crop biorefinery, a system in which a range of products are made from portions of grain and straw and in which both of these should be satisfactorily produced. In the present experiment, the effect of flax genotypes (7 varieties), cultivation sites (two locations) and seasons (two years) were tested with a standard randomized complete block design, in search of a compromise for the production performance for both grain and straw, with the aim of reintroducing flax back into the northern Italian environment. Overall, grain yield reaches an average value of about 1.4 t ha^{-1} (dw), while straw yield reaches 2.77 t ha^{-1} (dw). The former is strictly dependent on the environmental effects of the growing site and season, while the effect of genotype was not significant. The straw yield also depends on the second-order interaction of the factors analyzed, although the performance of three varieties, Festival, Solal and Linoal, was noteworthy and seemed to respond well in both environments. Overall, it was found that flax can be conveniently grown for both grain and straw production.

Keywords: linseed; energy crop; residual biomass; field agronomic performances

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1. Introduction

The political, economic and energy contingencies of recent years—such as the Kyoto Protocol, European legislation on renewable sources, new EU agricultural policies, climate change, growing energy demand, and the rising costs of fossil-based raw materials—have significantly boosted scientific research in the bioenergy sector [1–4]. Within this sector, the agricultural field plays a crucial role as a primary source of biomass, which consists of materials of animal and vegetable origin that have not undergone any fossilization process [5,6]. Agricultural biomass can be sourced either from the waste produced by conventional agricultural processes (residual biomass) or as the main product of these processes through so-called energy crops [7–10]. Energy crops appear to offer a promising solution to the growing need for diversification in surplus agricultural production [11,12]. However, the use of energy crops solely for energy production has recently been surpassed by the concept of "biorefinery". A biorefinery is an integrated system that includes chemical, physical or microbiological processes to convert biomass not only for energy purposes but also to produce materials and chemical compounds with high added value [13–17]. The VeLiCa project [18], financed by the Lombardy region in Italy, fits into this new context. Part of the project's aim was to investigate the potential of reintroducing an ancient crop of the North Italy regions, *Linum usitatissimum* L. (flax/linseed), into the Lombard environment for exploitation according to the biorefinery approach. The implementation of the research project involved achieving several key goals.

Among these tasks was an assessment of the agronomic performance of flax in the Lombard environment for the concurrent production of a significant amount of biomass (fiber plus shives) as straw, and a substantial quantity of grain for oil and meal production.

To achieve this goal, the research activity focused on evaluating the productive performance of various flax varieties to verify their adaptability to the environmental conditions of the region and their production potential, considering the growing season. The experimental plan, using a conventional randomized complete block design, considered the location, variety and year of cultivation as sources of variation by repeating the tests over two years. The production yields of straw and seed were assessed, and the results of this experiment are reported in the present paper.

This information gains new interest in light of the recent rediscovery of flax in the region, driven by some farms aiming for the full exploitation of this crop (https://www.bergamonews.it/2022/06/04/astino-la-fioritura-dei-campi-di-lino-a-bergamo-cresce-la-coltivazione-della-fibra/521226/, accessed on 10 May 2024; https://www.linificio.it/en/composite-materials/, accessed on 10 May 2024).

Despite flaxseed (linseed) not currently being a major crop in Lombardy's agricultural landscape, historically, flax cultivation played a significant role in the region's agrarian practices, particularly in textile production. Historically, flax was cultivated in Lombardy primarily for linen production rather than for its seeds. Flax cultivation for linen was important in various parts of Europe, including Italy, until the development of cotton and synthetic fibers became dominant. Flax was grown for its fibers, which were processed into linen, a highly valued textile in historical times.

Nowadays, Italian and EU agricultural policies might shift to support more diverse and sustainable crops. Subsidies and grants for flax cultivation could encourage farmers in Lombardy to adopt this crop, aligning with broader goals of environmental sustainability and agricultural diversification. Moreover, the current concept of biorefinery adds to this issue through its multipurpose character. The International Energy Agency (IEA) Bioenergy Task 42 defines biorefinery as "sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, and chemicals) and energy (fuels, power, and heat)", while according to the American National Renewable Energy Laboratory, "a biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass". This is fully compliant with a life cycle perspective, where the overall environmental impact strictly depends on the extent of the spectrum that a process chain can cover. Flax has the potential to be an affordable feedstock for the development of biorefineries in Lombardy.

2. Materials and Methods

Agronomic tests were conducted in two locations in Lombardy through field trials set up according to a randomized complete block design, applied in triplicate. In these two environments, seven different flax varieties were assessed over two consecutive years, 2011 and 2012.

2.1. Location, Soil, Climate, and Plant Material

The details of the two localities are summarized in Table 1. They belong to the municipality of Treviglio in the province of Bergamo (Italy) and in the municipality of Cavriana in the province of Mantova (Italy). These localities were chosen because they are representative of heterogeneity of the Lombardy environment.

Table 1. Main details of the two tested localities.

	Treviglio (BG)	Cavriana (MN)
Geographic coordinates *#	N 45°32′43″; E 9°35′00″	N 45°18′49″; E 10°36′43″
Position *#	flat	flat
Altitude (m asl) *#	125	70
Temperature max (°C) *#	35	33
Temperature average (°C) *#	14	12
Temperature min (°C) *#	−11	−9
Humidity (%) *#	70	71

Table 1. *Cont.*

	Treviglio (BG)	Cavriana (MN)
pH	7.6	8.4
Soil texture (%) $^{\lambda}$	sand: 62.5 silt: 18.0 clay: 19.5 type: sandy-clay	sand: 64.5 silt: 20.0 clay: 15.5 type: sandy-silt
Organic matter %dw $^{\lambda}$	0.60	0.86
Nitrogen (g/100 g) $^{\lambda}$	0.10	0.12
N ammonia (mg/kg dw) $^{\lambda}$	14.00	27.1
N nitric (mg/kg dw) $^{\lambda}$	6.05	19.5
P_2O_5 (mg/kg dw) $^{\lambda}$	149.00	688
K_2O (mg/kg dw) $^{\lambda}$	119.00	150

Note: * average data over the area; # average data over the last four years; $^{\lambda}$ measured data.

The main meteorological data, specifically significant temperatures (maximum, minimum and average) and the amount of precipitation, were continuously monitored throughout the entire crop cycle using dedicated electronic control units placed near the experimental plots. These units were programmed to acquire values on an hourly basis (Table 2). The following seven varieties of flax were assessed: Kaolin, Linoal, Natural, Valoal, Festival, Merlin, and Solal. All varieties were of French origin, with seeds supplied by Semfor (Italy).

Table 2. Rain and temperature average data recorded in the two tested environments over the two consecutive seasons.

Rain (mm) [a]						
	2011		2012		Average over 2013–2023 for Treviglio [c]	
	Cavriana	Treviglio	Cavriana	Treviglio	95.0% Uper Confidence Limit	95.0% Lower Confidence Limit
March	77.8	66.2	0.4	1.6	105.8	12.4
April	3.4	15.0	88.6	155.0	98.2	45.3
May	20.8	106.2	84.2	95.6	168.4	67.7
June	90.2	170.2	23.4	86.2	120.3	30.7
July	40.0	126.4	4.6	28.0	117.1	41.1
August	15.4	69.0	18.0	15.8	115.4	44.0
September	45.6	115.5	112.4	90.0	113.7	28.4
Total	293.2	668.5	331.6	472.2	-	-
Temperature (C°) [b]						
	2011		2012		Average over 2013–2023 for Treviglio [c]	
	Cavriana	Treviglio	Cavriana	Treviglio	95.0% Uper Confidence Limit	95.0% Lower Confidence Limit
March	9.0	9.9	13.9	14.1	16.1	11.9
April	16.0	17.4	12.7	12.3	21.0	17.1
May	20.1	19.8	18.1	17.8	25.2	20.5
June	22.0	22.2	23.5	22.7	32.0	26.2
July	23.4	23.5	25.2	24.0	32.7	28.2
August	25.4	26.0	26.0	24.8	31.8	27.4
September	22.0	21.8	19.9	18.9	26.9	23.2
Mean	19.7	20.1	19.9	19.3	-	-

Note: [a] Cumulative data recorded with minimum 0.2 mm increment; [b] Data recorded with bihourly frequency, subsequently averaged on a monthly basis; [c] Data gathered from the weather station "Centro Meteo Treviglio" (https://www.meteotreviglio.com/, accessed on 10 May 2024).

2.2. Experimental Procedure

The experimental fields were set up on two arable farms, each typical of its respective area. Table 3 summarizes the agronomic details and management practices applied during the experiment. In both locations and for the two years of testing, two main plots of land, each with a surface area of about 1600 square meters, were identified and delimited. Each main plot was further subdivided into three homogeneous sectors (blocks) of equal surface area, which were then subdivided into seven experimental plots (110 m^2 each, one per variety within each block). This setup allowed for a reliable application of the randomized complete block design.

Table 3. Agronomic details and management practices applied during the experiment.

	Location			
	Cavriana		Treviglio	
Season	2011	2012	2011	2012
Crop precession	corn		barley–soy	corn
Pre-seeding tillage	spring plowing at 30 cm + 2 harrowing			
Date of sowing	31 March	14 March	31 March	14 March
Orientation	north–south			
Parcel size and planting layout	19.8 m^2; 10 rows 11 m long, spaced at 0.16 m			
Investment	600 seed m^{-2}			
Pre-sowing fertilization	15 March N: 58 kg P_2O_5: 69 kg K_2O: 90 kg	3 March N: 69 kg P_2O_5: 83 kg K_2O: 72 kg	absent - - -	
Top dressing	03 May N: 67 kg	30 April N: 50 kg	03 May N: 54 kg	2 May N: 67 kg
Pre-emergence weed control	Afalon DS 0.7 L ha^{-1}, manual distribution			
Post-emergence weed control	1		2	1
Pesticide treatments	absent			
Irrigation	surface flooding n° 3 intervention		surface flooding n° 4 intervention	

The soil of the experimental plots was prepared following conventional agronomic practices, including autumn plowing, harrowing at the end of winter, and later refinement near sowing. Sowing was conducted mechanically using a universal seed drill for linseed. In both locations, irrigation and weeding interventions were necessary.

After sowing, the development of the crop was monitored through numerous inspections, which allowed for the estimation of the timing of the main phenological phases of the growing cycle (emergence, flowering and ripening) (Table 4).

Table 4. Main phenological phases of the growing cycle.

	Number of Days from Sowing			Vegetative Period (Days)	Flowering Period (Days)
	Emergence	Flowering	Ripening		
Sowing on 31-March-2011					
Cavriana	14	61	102	47	23
Treviglio	21	92	151	71	18
Sowing on 14-March-2012					
Cavriana	27	71	116	44	17
Treviglio	22	81	135	59	22

The vegetative period was calculated as the number of days between emergence and the beginning of flowering observed in the field (i.e., "flowering" minus "emergence" in the table). The flowering period corresponds to the number of days between the beginning of flowering and the end of flowering observed in the field.

At maturity, above-ground biomass produced from the experimental plots was entirely collected, thus allowing estimation of the potential yields. Harvest was conducted mechanically by two successive steps. In the first step, the plants were cut using a sickle bar mower and then collected manually. In the second step, the separation of the seed was carried out by means of a fixed-point thresher. At the same time as the harvesting operations, a sampling of whole plants taken from each plot was carried out. Specifically, two sampling areas (0.5 m length × 0.6 m wide) per plot were collected.

Then, 10 plants were randomly subsampled and used to determine the biometric traits, as described in Masella et al. [19]. The following traits were measured and/or assessed through plant sampling: plant density (plants per m^2), total above-ground biomass (t ha^{-1} dw), straw yield (t ha^{-1} dw), potential seed yield (t ha^{-1} dw), grain yield (t ha^{-1} dw), seed moisture (percentage by weight), average plant height (mm), average height of the first branch (mm), average height of the first capsule (mm), basal stem diameter (mm), average number of basal branches per plant, average number of apical branches per plant, average number of capsules per plant, average weight of capsules per plant (g), and harvest index (dimensionless).

The straw resulting from the thresher was entirely collected and weighed after drying in a mechanically ventilated oven at 105 °C, allowing for the assessment of straw production per unit area. Seeds were air-dried at 30 °C in a ventilated chamber until they reached 8% seed moisture. The resulting seed or straw yield per plot was then converted to a hectare basis and expressed as t ha^{-1}.

2.3. Statistical Analysis

The standard ANOVA procedure for a randomized complete block design (RCBD) was applied. The statistical model behind the (RCBD) is an extension of the basic analysis of variance (ANOVA) model. In RCBD, the variation in the response variable is partitioned into three main sources:

1. Treatment effect: This accounts for the differences between the treatments being compared.
2. Block effect: This represents the variation among the blocks, which are groups of experimental units that are similar in some aspect but may differ from one another.
3. Error term: This captures the random variability or unexplained variation within each block.

Mathematically, the model can be represented as the following:

$$Y(ij) = \mu + \tau\_i + \beta\_j + \varepsilon(ij)$$

where

- Y(ij) is the response variable for the (i)th treatment in the (j)th block;
- μ is the overall mean;
- τ_i is the effect of the (i)th treatment;
- β_j is the effect of the (j)th block;
- ε(ij) is the random error term.

Analysis of variance techniques are generally used to test the significance of treatment effects, block effects and their interactions. Only when the ANOVA gave significance of the effects of the investigated factors or their interaction (of first- or second-order), multiple pair comparisons of treatment means were investigated for significance adopting Tukey's honestly significant difference (HSD) post hoc test (*p*-value of 0.05) or Tukey's b test.

3. Results and Discussion

The seasonal trend of rainfall differed both in terms of the cultivation location (Cavriana versus Treviglio) and the test year (2011 versus 2012) (Table 2). The differences are evident in the total rainfall, which was significantly higher in Treviglio in both test years, especially in 2011, when it was almost double that of Cavriana. In Treviglio, the highest rainfall in 2011 occurred in April, May and August, whereas in 2012, it was in June and July, highlighting the different trends linked to each test year. Specifically, Treviglio experienced significantly more rainfall in 2011 than in 2012, with the greatest differences observed in March, June and July. Conversely, April was noticeably rainier in 2012.

The total rainfall in Cavriana was remarkably similar for the two years, with a slight advantage of 30 mm in 2012. However, the rainfall distribution was quite different, appearing almost inverse when comparing the months. The highest rainfall in March, June, July and September of 2011 corresponded to the lowest rainfall in those same months in 2012. Regarding temperatures, the two locations and the two-year trial were substantially similar.

Table 5 summarizes all the measured parameters, regardless of the sources of variation considered, such as test year, location of cultivation and genotype. The values, along with the relative indices of dispersion (standard deviation and coefficient of variation), correspond to the average of the repetitions (3), locations (2), varieties (7), and test years (2), totaling 84 entries. Table 5 provides an overall view of the test results. The production responses appear favorable for both grain and straw, aligning well with the pre-established aim of the research to enhance both products.

Table 5. Grand mean values of agronomic and biometric parameters.

Parameter	Unit	Mean	Standard Deviation	Coefficient of Variation
Grain yield	t ha^{-1} dw	1.399	0.681	49
Straw yield	t ha^{-1} dw	2.769	0.871	31
Plant density	n plant m^{-2}	387	79	20
Total above-ground biomass	t ha^{-1} dw	6.363	1.827	29
Potential seed	t ha^{-1} dw	1.907	0.805	42
Seed moisture	% w w^{-1}	7.0	1.4	20
Average plant height	mm	611.6	93.0	15
Average height first branch	mm	377.1	81.2	22
Average height of first capsule	mm	463.5	70.1	15
Basal stem diameter	mm	2.4	0.9	38
Average number of basal branches per plant	n	1.5	0.7	51
Average number of apical branches per plant	n	9.1	3.2	35
Average number of capsules per plant	n	27.6	19.4	70
Average weight of capsules per plant	g	1.23	0.62	50
Harvest index	dimensionless	0.3	0.1	30

As a general indication [20], "flax for fiber" is usually grown with remarkably high sowing densities (greater than 1500 plants per square meter) to produce thin (basal diameter less than 2 mm), long (height around one meter), and unbranched stems. In such cases, seed production is limited and typically much lower than one ton per hectare, while straw production can range from 5 to 7 tons per hectare. Conversely, for "linseed for oil", sowing densities of around 500 plants per square meter are used, with relatively wide row spacing (20–30 cm) to encourage strong branching, both basal and apical.

In the present study, an intermediate configuration was adopted with a low plant density (potential sowing density of 600 seeds per square meter) and relatively limited row spacing (16 cm). As shown in Table 5, this approach resulted in relatively small plants (about 60 cm tall), moderately branched, with a considerable basal diameter (greater than 2 mm). Under these conditions, seed yield was satisfactory, exceeding 1.20 tons per hectare, and straw production reached 3.0 tons per hectare.

It is noteworthy that the analyzed parameters exhibited high variability, with some coefficients of variation exceeding 50%. For instance, the number of capsules per plant had a coefficient of variation over 70%.

This result is likely linked to the strongly plastic nature of flax, which can vary its phenotypic response according to changing environmental conditions. Overall, the productive performances assessed in this study align with other investigations, particularly regarding grain yield. Angelini et al. [21], in Italy, reported an average seed production of about 1.15 t ha^{-1} as the grand mean over two types of locations (lowland and hilly) and three successive seasons. The grand mean of grain yield measured in the present study was close to that value, at about 1.4 t ha^{-1}. However, straw production performed comparatively worse, with about 2.8 t ha^{-1} versus 5.5 t ha^{-1} reported by Angelini et al. [21].

Tavarini et al. [22], also in Italy, reported actual seed yields ranging from 0.6 t ha^{-1} to 1.39 t ha^{-1}, corresponding to an overall mean slightly lower than the present value (about 0.92 t ha^{-1}). In their case, straw production performed better than in the present study, with an average value of about 5.1 t ha^{-1}. The occurrence of lower straw production and higher seed yield compared to the literature is confirmed in reports from outside Italy. Bauer et al. [23] reported a rough average straw production of about 5.50 t ha^{-1} and a seed yield of 0.82 t ha^{-1} in the Southeast USA. Similarly, Rashwan et al. [24] reported about 10.00 t ha^{-1} of straw and 0.88 t ha^{-1} of seed yield. Dey et al. [25] reported a straw yield of about 6.9 t ha^{-1}. Interestingly, data from the Flax Council of Canada [26] closely resemble the present work, with reported seed and straw yields of about 1.20 t ha^{-1} and 0.73 t ha^{-1}, respectively (results of some plot trials from 2008 to 2011).

In the present study, the results of the ANOVA for grain yield (Table 6) indicate a lack of significant genotype effect, while the significant effects of the locality and the year of cultivation are evident. As depicted in Figure 1—Graph A on the left, 2012 offered more favorable conditions than 2011, with Cavriana exhibiting better performance compared to Treviglio (Figure 1—Graph A on the right).

Table 6. ANOVA results for flax/linseed grain yield and straw yield.

Results for Grain Yield		
Source of Variation	***p*-Value**	**Statistical Significance ($p \leq 0.05$)**
Block	0.086	no
Year	0.000	yes
Locality	0.000	yes
Variety	0.636	no
Year × Locality	0.827	no
Year × Variety	0.648	no
Locality × Variety	0.683	no
Year × Locality × Variety	0.170	no
Results for Straw Yield		
Source of Variation	***p*-Value**	**Statistical Significance ($p \leq 0.05$)**
Block	0.650	no
Year	0.142	no
Locality	0.000	yes
Variety	0.000	yes
Year × Locality	0.000	yes
Year × Variety	0.172	no
Locality × Variety	0.010	yes
Year × Locality × Variety	0.226	no

For straw productivity, Table 6 summarizes the effects of the factors. The location effect is significant and varies with the year, as indicated by the significance of the interaction (Figure 1, Graph B). Additionally, the varietal effect is significant and varies with locality, as demonstrated by the significance of the interaction (Figure 1, Graph C).

For the genotype effect, the differences illustrated in Figure 1 (Graph C) were evaluated using "Tukey's HSD" test. This test categorizes the analyzed cases into homogeneous sub-groups where the members do not significantly differ from each other, while the mean of one group significantly differs from the means of other groups. The best performances were observed in Festival and Solal at Cavriana, forming the first group. An interesting result was observed for Natural, which appeared twice in the second group, indicating good productions in both locations, possibly due to its adaptability to variable environmental conditions.

In summarizing the results for the crop's productivity responses, it is crucial to highlight the importance of the environmental factor, expressed through both the variability induced by different cultivation sites and the seasons. Productivity was significantly higher at Cavriana, while 2012 offered more favorable conditions than 2011.

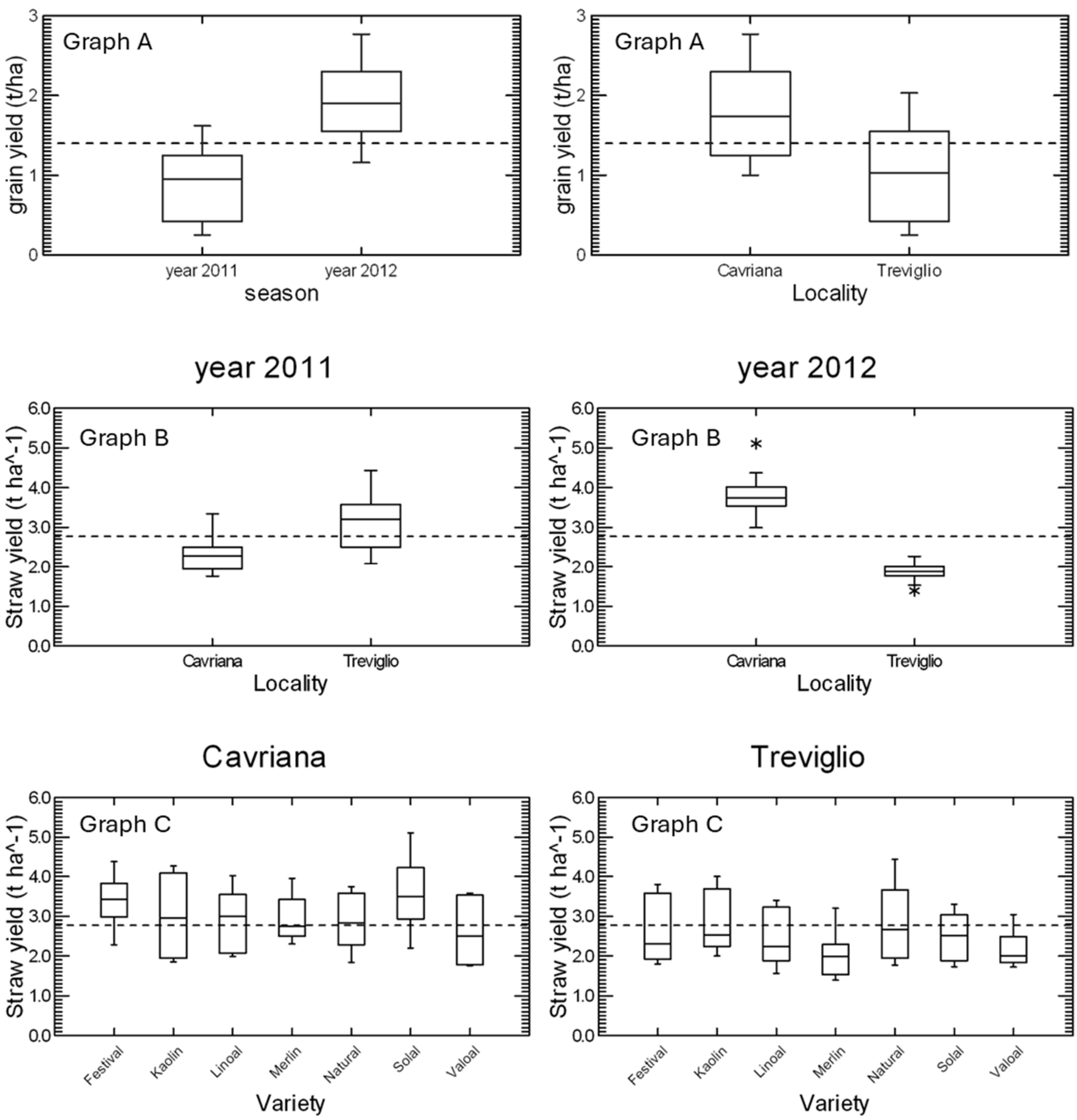

Figure 1. Box-plot of grain yield as affected by the main effects of locality of cultivation and season (Graph A); straw yield as affected by the interaction of locality of cultivation and season (Graph B); box-plot of straw yield as affected by the interaction of locality of cultivation and variety (Graph C); * indicate outlier values.

In addition to the varying meteorological conditions between the two locations over the two-year trial period, the diversity of environmental conditions can also be attributed to the physical characteristics of the two localities. It is helpful to consider certain soil characteristics traditionally deemed favorable for flax production, such as a preference for medium-textured (loam) or light soils, with ample organic matter, deep profiles and good drainage. Water stagnation and excess nitrogen should be avoided. From the data presented in Table 1, the soil of Cavriana appears to offer more favorable conditions for cultivation due to its lighter texture, characterized by a higher sandy fraction and lower clay content, thereby ensuring better drainage. Moreover, it possesses a higher organic matter content, as well as greater levels of phosphorus and potassium. These soil characteristics likely contributed to the superior results observed in cultivation near Cavriana.

The abundant water availability that characterized the growth cycle of the flax varieties cultivated in Treviglio in 2011 resulted in an extension of the vegetative phase of the crop at the expense of the reproductive phase. Conversely, in 2012, rainfall in Treviglio was significantly lower than the previous year, particularly from May to July. This likely facilitated a more consistent progression of the flowering and seed filling phases leading up to maturity.

Confirmation of the significance of water availability during the growth cycle is evident in the results of linear correlation analysis conducted between monthly weather parameters and the duration of flowering and vegetative periods. A strong positive linear association was observed between the length of the vegetative period and the total amount of rainfall (r = 0.98), particularly for the months of June, July and August (r ranging from 0.84 to 0.89). In contrast, the length of the flowering period exhibited a less strict association with rainfall, showing a negative correlation with a maximum r value of −0.62.

Similarly, the same approach was employed to assess the degree of linear association between the weather patterns and productive performances, specifically the correlation between monthly temperature and rainfall with grain and straw production. According to Table 7, grain yield is significantly influenced by rainfall, particularly in June and July, coinciding with the flowering period, showing a negative correlation ($r \geq -0.9$).

Table 7. Correlation coefficients (Pearson) between rainfall or temperature (monthly basis), and flax/linseed grain yield and straw yield.

	Rainfall		Temperature	
	Grain Yield	**Straw Yield**	**Grain Yield**	**Straw Yield**
March	−0.73	−0.12	0.70	0.09
April	0.53	−0.21	−0.82	0.06
May	−0.11	0.23	−0.68	−0.02
June	−0.94	−0.20	0.81	0.48
July	−0.90	0.03	0.83	0.54
August	−0.75	0.26	−0.07	0.78
September	0.04	0.54	−0.61	0.13
total/mean	−0.70	0.02	−0.30	0.68

Indeed, precipitation appears to have an impact on flowering. Overall, an excess of water seems to negatively affect grain production, whereas straw production seems to be less sensitive, as indicated by the reduced values of correlation coefficient (r).

Regarding temperature, its effect on grain production varies with the months. There is a negative correlation during the crop's development in April and May, followed by a positive correlation in June and July, coinciding with the end of the vegetative period and flowering. Once more, straw yield appears to be less sensitive, displaying a high positive correlation only during August.

In consideration of the significance of precipitation, we examined the short-term rainfall patterns over a span of ten years from 2013 to 2023. Average temperature and rainfall values computed over this period, along with their 95% confidence limits, were documented in Table 2 to facilitate a direct comparison with experimental data. Unfortunately, this comparison was only feasible for Treviglio, as data for Cavriana were not available. Nevertheless, the experimental pattern closely resembles the short-term trend, with the average values from the experiment falling entirely within the confidence interval limits.

The genotype factor did not exhibit significant differences for grain yield, whereas significant differences were observed for straw yield. Particularly noteworthy was the statistically significant interaction between the test environment and the variety, indicating that the varietal effect is not consistent but varies with changing environmental conditions.

This variability could be attributed to the dual-purpose nature of the selected varieties and the heightened sensitivity of biological yield components other than seeds to environmental factors. Consequently, the degree of genetic effects on various biometric traits under changing environmental conditions might be more pronounced for straw than for seeds.

4. Conclusions

The trials have revealed satisfactory productive performance for flax, with weather patterns, particularly rainfall, playing a pivotal role. The disparity in rainfall between the two locations over the two test years was evident. In terms of genotype effects, the performance of three varieties—Festival, Solal and Linoal—stood out notably for straw production and demonstrated resilience in both environments. Furthermore, we demonstrated that the weather conditions during the experiment fell within the short-term variation observed over the past 10 years in one of the tested locations.

Overall, this study indicates that flax can be effectively cultivated for both grain and straw production, with grain yield averaging about 1.4 t ha^{-1} (dw) and straw yield reaching 2.77 t ha^{-1} (dw). Both traits exhibited considerable variability, with overall variation coefficients of 49% and 31%, respectively.

One limitation of the present study is the absence of fiber extraction, quantification, and characterization, as well as shive quantification and assessment of the oil content of the grain. Additionally, different cultivation strategies could have potentially optimized the overall productivity or highlighted better performance of specific genotypes. These aspects warrant consideration in future research.

The primary shortcoming likely lies in the time gap between the commencement of the experiment and the publication of the results. However, as outlined in the introduction, there has been renewed interest in flax and its multipurpose potential in the studied region since 2021. Several new projects are underway (https://www.chimicaverdelombardia.it/progetto-biomass-hub/, accessed on 10 May 2024), ensuring the relevance of the data and results of this work.

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